NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 1-89

OXYGEN CONSUMPTION RATE OF OPERATIONAL UNDERWATER SWIMMERS

LCDR M.E. KNAFELC, MC, USN

JANUARY 1989

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CONTENTS

ABSTRACT

Prior to evaluating an underwater breathing apparatus (UBA), diver performance must be determined. Previous studies determining the oxygen consumption of swimming and resting divers were done in the laboratory and were limited in scope. Criticisms of those studies suggested that they may not have accurately simulated the underwater work expected of an operational diver. This study measured the oxygen consumption $\dot{V}O_2$ sustained by experienced Special Warfare (SPECWAR) operators participating in training exercises. By using a closed-circuit oxygen underwater breathing apparatus, the decrease in the oxygen bottle pressure reflected the amount of oxygen consumed by the diver. Combat swimmers, swimming at their own pace, had a mean $\dot{V}O_2$ of 1.5 ± 0.2 (SD) liters per minute (lpm), (n=8). Resting divers mean $\dot{V}O_2$ was $0.64 \pm .09$ (SD) lpm (n=12). These values are comparable to the results of the previous studies. Guidelines reflecting underwater oxygen consumption and estimating carbon dioxide production for calculating carbon dioxide canister duration should be based on the results of these studies.

KEY WORDS:

oxygen consumption

canister duration

exercise

closed-circuit UBA

Draeger LAR V

I. INTRODUCTION

Prior to evaluating an underwater breathing apparatus (UBA), diver performance must be determined. This effort began in 1954 with an oxygen consumption study performed at the Navy Experimental Diving Unit (NEDU). Divers wearing swim suits in 78 °F (24.9 °C) water swam measured laps underwater in a 80 by 40 foot pool using the Lambertsen Amphibious Respiratory Unit (LARU), a closed-circuit oxygen underwater breathing apparatus (UBA), (1). The decrease in the oxygen bottle pressure reflected the oxygen consumed by the diver. The investigators limited their study to determining an efficient underwater swim speed and its associated oxygen consumption rate. Swim efficiency was defined in terms of distance covered per unit of oxygen consumed. Exercise lasted from 10 to 50 minutes depending on the swim speed. The data for each swim was accepted if the rate of the oxygen bottle pressure drop stabilized indicating steady state. Average efficiency was reported as almost constant for speeds up to 0.8 knots. However, the endurance of the diver and the effect of fatigue on efficiency were not explored when swimming greater than 50 minutes. In addition, the study did not address the oxygen consumption rate of a diver when allowed to pace himself.

Using the data obtained in that study, testing criteria for UBA carbon dioxide absorbant canisters was developed. Based on a swim speed of 0.8 knots maintained for 30 minutes, it was estimated that a diver would consume between 1.5 to 1.6 liters per minute (lpm) of oxygen. The ratio of CO_2 production to O_2 consumption is the respiratory quotient (R). For unmanned canister duration studies, an R of 1.0 was assumed (2). Though the study served as a starting point, its limited scope may fail to project diver performance during a swim longer than one hour.

Zumrick in 1984 measured the oxygen consumption of resting divers (3). That study looked at five divers wearing a dry suit, the Passive Diver Thermal Protection System, in 56 °F (13.4 °C) water at a simulated depth of 65 feet of seawater (FSW). An average oxygen consumption rate measured was 0.64 lpm.

Criticisms of the previous studies suggested that they may not have accurately simulated the underwater work expected of an operational diver. Therefore, this study was conducted in the field using Special Warfare (SPECWAR) divers participating in training exercises for combat swimmers and SEAL Delivery Vehicle (SDV) operators. With the oxygen consumption measured in this study and Thalmann et al. having measured an R of 0.9 during submerged submaximal work at depth (4), more realistic carbon dioxide values can be calculated. By using these values, CO2 absorbant canister duration limits and the unmanned canister testing criteria can be adjusted to reflect actual manned data.

II. METHODS

A. SUBJECT SELECTION

Eight Navy SPECWAR divers were used as test subjects for determining the oxygen consumption of working divers. Nine qualified SPECWAR SDV divers were used for the resting diver scenario. All subjects were experienced operators familar with closed-circuit oxygen UBAs. Using trained SPECWAR divers eliminated training requirements and minimized such variables as fear, UBA off-gassing, and improper buoyancy and trim which can be a problem with inexperienced divers. All these factors can affect the oxygen consumption estimation.

Data on each subject (age, height, weight, percent body fat by skin fold thickness) were recorded and listed in Table 1.

B. EQUIPMENT

The Draeger LAR V (Draegerwerk Lubeck, Federal Republic of Germany), a chest-mounted diving apparatus, was used in this study. This is a closed-circuit oxygen UBA. Assuming no gas leaks, the decrease in the oxygen bottle pressure represents the oxygen consumed by the diver. The floodable volume of several oxygen flasks with the valves installed averaged 1.65 liters.

Additional equipment included: a calibrated 0 to 3000 psig pressure gauge accurate to 1/4 of 1% full scale (3-D Instruments, Royln, Anaheim, CA) to measure the oxygen bottle pressure, a surface thermometer to measure the bottle temperature, and a wet thermometer to measure the water temperature (YSI 700 series, Yellow Springs, OH).

C. FIELD CONDITIONS

The divers for the open water swim used a wet suit in 59 °F (15 °C) water. A 2-hour swim was performed by each of the eight divers. All divers carried neutrally buoyant ordnance on their back and were trimmed accordingly.

Using an SDV simulator in a training tank, the divers performed the SDV operations of pilot, navigator or passenger. All divers were wearing dry suits, either the TLS or EOD MK 1 Mod 0 dry suit (Diving Unlimited International, San Diego, CA) with Thinsulate® 400, polypropylene underwear and wet suit gloves. The water temperature was 55 °F (13 °C). Nine subjects performed a total of 12, 3-hour dives. The divers each performed only one dive per day.

D. PROCEDURES

All dive and safety briefs occurred prior to diving operations according to standard U.S. Navy procedures. The water temperature was recorded the day of the dive.

The Draeger LAR V UBAs were set up and leak tested in accordance with established pre-dive procedures. Upon completion, the oxygen bottle was turned off and removed from the test UBA. The oxygen bottle pressure and temperature was accurately measured and recorded along with the diver's name. The oxygen bottle was then attached to the test UBA, the oxygen valve opened and the diver made ready to enter the water. Since the test UBA was purged of nitrogen during the pre-dive set up, there was no need to add oxygen to purge the breathing loop. Because the oxygen exhausted during the diver purge procedure could not be accurately measured, the divers purged on a separate UBA and immediately switched to the test UBA while holding their breath. Timing of the dive started when the diver began breathing from the test UBA. The divers entered the water within 30 seconds of the start time.

Divers participating in the working diver study swam a planned course surfacing every 30 minutes for navigational sightings lasting no more than 15 seconds. The resting diver study was performed within the SDV training facility simulating SDV operations. The divers were instructed to observe and report any significant gas leaks. Upon completion of the dive, the oxygen bottle valve was turned off. The oxygen bottle pressure and temperature was measured post-dive. The bottle pressures were corrected to 20°C prior to calculating the oxygen consumption rate.

E. DATA ANALYSIS

Oxygen Consumption Calculation (5)

$$\dot{V}O_2 = \Delta P/t \cdot V_b/14.7\ \text{psig} \cdot 273/(T+273) \qquad \text{eq (1)}$$

where:

$\dot{V}O_2$ - oxygen consumption (lpm)
ΔP - oxygen bottle pressure change (psig)
t - time (minutes)
V_b - oxygen bottle's floodable volume (liters)
T - temperature (C)

The oxygen consumption rate means and standard deviations were reported for the swim and for the resting studies.

III. RESULTS

The combat swimmer oxygen consumption was 1.5 ± 0.2 lpm. When operating the SDV trainer, the oxygen consumption was $0.64 \pm .09$ lpm. The results of the individual dives are listed in Table 2. No significant amount of off-gassing was reported by the divers.

IV. DISCUSSION

New UBAs are being designed for long duration dives. Thus, it becomes increasingly important to determine the actual requirements of a typical underwater swimmer. The current operational requirements and UBA design parameters were based upon assumed work levels determined during short duration exercise. This current study attempted to appraise the metabolic rate sustained by experienced SPECWAR operators performing long duration swims or SDV operations.

The combat swimmers, swimming at their own pace, had an oxygen consumption of 1.5 lpm. This was similar to the projected consumption rate from the Dwyer and Lanphier 1954 study (1). The oxygen consumption rate of 0.64 lpm for the resting scenario duplicated the rate obtained in the Zumrick study (3).

Studies performed on the surface measured R between 0.7 and 0.8 for moderate work (6). However, Thalmann, et al., measured an R of 0.9 for a diver performing moderate to heavy work (3). Because there may be an effect of water immersion on the respiratory quotient, the more conservative R of 0.9 is appropriate to estimate CO_2 production. It is doubtful that the diver's R would exceed 0.9 during most diving operations. Thus, using an R of 1.0 may be overly conservative.

Using the oxygen consumption rate determined in this study, and assuming an R of 0.9, the carbon dioxide production rate should be adjusted. To evaluate an unmanned CO_2 canister duration or to calculate the canister time limit for an operational dive, the rest values are a $\dot{V}O_2$ of 0.64 lpm and a $\dot{V}CO_2$ of 0.58 lpm. The work values are a $\dot{V}O_2$ of 1.5 lpm and a $\dot{V}CO_2$ of 1.35 lpm.

V. CONCLUSION

Based on the results of these studies, guidelines should be developed that reflect underwater oxygen consumption and estimated carbon dioxide production for calculating carbon dioxide canister duration. The resting $\dot{V}O_2$ is 0.64 lpm, the swimming $\dot{V}O_2$ is 1.5 lpm. Guidelines for the unmanned testing of carbon dioxide canister duration should reflect the actual underwater oxygen consumption exhibited by resting and working divers.

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TABLE 1

DIVER'S PHYSICAL CHARACTERISTICS

Diver	age	height (inchs)	weight (lbs)	%body fat (7)
1	20	72	180	16
2	26	72	180	12
3	29	69	170	21
4	31	70	175	23
5	28	72	190	17
6	24	71	155	13
7	20	73	210	18
8	36	70	170	17
9	28	68	165	12
10	30	67	177	20
11	28	68	152	16
12	32	66	147	18
13	28	69	194	13
14	27	70	171	14
15	29	71	170	12
16	43	70	173	16
17	31	71	216	23
mean ± S.D.	29 ± 5	70 ± 2	176 ± 18	17 ± 4

TABLE 2

OXYGEN CONSUMPTION OF THE COMBAT SWIMMER

Diver	Time	O_2 pressure drop	$\dot{V}O_2$
1	120	1393	1.21
2	120	1970	1.71
3	120	2020	1.76
4	120	1660	1.44
5	120	1030	1.44
6	120	1626	1.40
7	120	1673	1.46
8	120	2040	1.77
		mean	1.52 ± 0.2

OXYGEN CONSUMPTION OF THE SDV OPERATOR

Diver	Time	O_2 pressure drop	$\dot{V}O_2$
9	183	1090	0.63
10	184	1290	0.74
11	186	945	0.54
12 (dive 1)	179	955	0.56
12 (dive 2)	171	962	0.60
13 (dive 1)	177	1240	0.74
13 (dive 2)	109	773	0.74
14 (dive 1)	159	907	0.60
14 (dive 2)	169	1156	0.70
15	155	843	0.57
16	149	1050	0.73
17	145	690	0.49
		mean	0.64 ± .09